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Transverse photon spin beyond interfaces

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Photons possess spin degree of freedom, corresponding to the rotating direction of the field vectors. Photon spin plays an important role in various applications such as optical communications, information processing and sensing. In conventional isotropic media, photon spin is aligned with the propagation direction of light, obeying spin momentum locking. Interestingly, at certain interfaces, the surface waves decaying away from the

interface possess a photon spin transverse to its propagation, opening exciting opportunities for observation of spin dependent unidirectional excitation in confined systems. Here we propose and realize transverse photon spin (T-spin) in the interior of a bulk medium, without relying on the presence of any interfaces. We show the mapping of the T-spin of the surface modes to that of the bulk modes by introducing the coupling between electric and magnetic responses along orthogonal directions, i.e., bianisotropy, into the medium. We further discover that an interface formed by two bianisotropic media of opposite orientations supports edge-dependent propagating modes with tunable cutoff frequencies. Our results provide a new platform for manipulating the spin orbit interaction of electromagnetic waves.

In recent years, spin Hall effect (SHE) of light has attracted growing attention¹⁻¹⁹, because of its great potential in facilitating novel nanophotonic and quantum applications²⁰⁻²⁶. As counterpart of SHE in solid-state physics, spin-orbital interaction of light produces spin-dependent transport of photons in systems under time reversal symmetry (T-symmetry)^{1,2}. In free space, the spin angular momentum (SAM) of the left-handed circular polarized (LCP) or right-handed circular polarized (RCP) is oriented along the direction of $\pm \bar{k}$ with \bar{k} being the wavevector, as constrained by the transversality condition $\bar{k} \cdot \bar{D}=0$ and $\bar{k} \cdot \bar{B}=0$, where \bar{D} represents the electric displacement and \bar{B} stands for the magnetic flux density²⁷. Remarkably, the SAM of light in most confined systems is orthogonal to the propagation direction, leading to the so-called transverse spins (T-spins), with electric field (\bar{E}) or magnetic field (\bar{H}) containing non-zero longitudinal component parallel to \bar{k} ²⁸⁻³⁰. Respecting the T-

symmetry, the SAM of a T-spin changes its sign when the propagation direction is reversed. This feature has been exploited in many important applications in the radio frequency and optical regimes, such as asymmetric scattering, directional spontaneous emission, spin-controlled radiation, and wave guiding³¹⁻³⁶.

Constructing the T-spins requires the electric/magnetic field to rotate in the plane containing wave vector (\vec{k}), which does not usually occur for plane waves propagating inside conventional medium. Thus, T-spin has been mostly realized for evanescent electromagnetic (EM) fields in confined systems^{18,19,29,30}, with surface plasmonic polariton (SPP) as one of the most well-known examples². For an SPP wave, its wavevector on each side of the interface can be expressed as $\vec{k}_{//} + i\vec{k}_T$ (with $\vec{k}_{//} \cdot \vec{k}_T = 0$), which, from the transverse wave condition, leads to a rotating field in the plane of wave propagation. The direction of the SAM is therefore perpendicular to the propagation direction of the surface wave. However, the SPP based T-spins are very limited in broad application scenarios, wherein external confinements should be lifted. For instance, chiral quantum optics requires for three-dimensional T-spin dynamics in unbounded systems¹. However, presence of a T-spin in a medium without any confinements has not been discovered till now.

Here we show that T-spins can exist in bulk state of the wave without involving evanescent component. Specifically, we propose a physical mapping of T-spin from surface modes to the bulk modes in homogeneous metamaterials. We show that the essential magneto-electric (ME) coupling along orthogonal directions (i.e. the bianisotropy) plays the same role as the evanescent wave vectors in generating the T-spin. Experimentally, we observe the bulk wave's T-spin and the corresponding asymmetric scattering. Further, we investigate the interesting

wave guiding effect through T-spin cancellation on interfaces formed by two metamaterials with opposite T-spin bulk modes. The transport of such interface modes is shown to be highly robust against sharp bendings.

T-spins beyond an Interface

We start by reviewing the formation of T-spin in SPP waves. SPP wave is supported at the interface between a dispersive metal and air, as shown in Fig. 1a. It propagates along the interface with a complex wave vector, i.e. $\bar{k}_{spp} = k\hat{x} + i\sigma\hat{y}$ where k and σ are real. Accordingly, \bar{E} and \bar{H} fields of the SPP can be written as $\bar{E} = \hat{x}E_x + \hat{y}E_y$ and $\bar{H} = \hat{z}H_z$. On the air side, the divergence of \bar{D} vanishes, leading to $kE_x + i\sigma E_y = 0$. Thus, there is a phase difference of $\pm\pi/2$ (depends on the sign of σ) between E_x and E_y , resulting in a rotating \bar{E} field in the x - y plane, i.e. an electric T-spin along z direction.

Suppose such a T-spin can also be excited inside a homogenous medium without the presence of an interface, as shown in Fig. 1b. Without losing generality, assuming the bulk mode is propagating along x direction, i. e. $\bar{k}_{bulk} = k\hat{x}$. A direct mapping from the transversality condition $\bar{k} \cdot \bar{D} = 0$ in the bulk medium to that of SPP $k(E_x + i\frac{\sigma}{k}E_y) = 0$ requires that $D_x = \varepsilon_0(E_x + i\frac{\sigma}{k}E_y)$ with ε_0 being the free space constant. The above equation indicates that the medium shall be anisotropic with $\varepsilon_{xy} = i\frac{\sigma}{k}\varepsilon_{xx}$ ($\bar{\varepsilon}$ is the permittivity tensor) in the absence of bianisotropy, i.e. there is no coupling between electric and magnetic responses. However, this constitutive relation does not exist in those lossless and

reciprocal media, whose $\bar{\bar{\epsilon}}$ should be real and symmetric.

Interestingly, this problem can be solved if the medium possesses bianisotropy. Applying $\nabla \times \bar{E} = i\omega \bar{B}$ to the SPP wave, one obtains $kE_y = i\sigma E_x + \omega\mu_0 H_z$. Hence $\bar{k}_{spp} \cdot \bar{D} = 0$ can be rewritten as $k[(1 - \frac{\sigma^2}{k^2})E_x + \frac{i\sigma\omega\mu_0}{k^2}H_z] = 0$, which, mapped to the bulk medium, is equivalent to the constituent equation $D_x = \epsilon_0[(1 - \frac{\sigma^2}{k^2})E_x + \frac{i\sigma\omega\mu_0}{k^2}H_z]$. The relationship between H_z and D_x indicates that the electric-magnetic coupling, i.e. bianisotropy, is essential for a bulk medium to support T-spins. Thus, a one-to-one mapping of the T-spin between an SPP mode and a bulk mode in a bianisotropic medium is established.

For a lossless and reciprocal bianisotropic medium, the general constitutive relation can be written as $\bar{B} = \bar{\bar{\mu}} \cdot \bar{H} + i\bar{\bar{\chi}} \cdot \bar{E}$ and $\bar{D} = \bar{\bar{\epsilon}} \cdot \bar{E} - i\bar{\bar{\chi}}^T \cdot \bar{H}$, with $\bar{\bar{\mu}}$ and $\bar{\bar{\chi}}$ being the permeability and the magnetoelectric (ME) tensors, respectively. For a wave with T-spin along z direction (both the rotating electric field and the propagation direction are in the x - y plane, as indicated in Fig. 1c), the medium must possess mirror symmetry with respect to the x - y plane. With the symmetry consideration, it can be proved that the constitutive tensors are greatly simplified, with the only nonzero elements of $\bar{\bar{\chi}}$ being χ_{zx} and χ_{zy} , and that bianisotropy is the only key ingredient required in generating the T-spin for a medium obeying time reversal symmetry. The corresponding transverse angular momentum of the bulk modes can be written in a form $\bar{S} = \frac{\epsilon_0 |H_z|^2}{2\omega^2 \cdot \det[\bar{\bar{\epsilon}}_T]} (\bar{k} \times \bar{C})$, with $\bar{\bar{\epsilon}}_T = \begin{bmatrix} \epsilon_{xx} & \epsilon_{xy} \\ \epsilon_{yx} & \epsilon_{yy} \end{bmatrix}$ and \bar{C} being a bianisotropy vector given by $\bar{C} = \hat{x}\chi_{zy} - \hat{y}\chi_{zx}$. To have a non-zero \bar{C} , the medium studied shall lack any C_ν ($\nu \geq 2$) rotational symmetry in the plane perpendicular to \hat{S} (Supplemental

material). A purely magnetic T-spin can also be constructed through a similar procedure, for which a similar ME coupling is required. In Fig. 1d, we show the spatial dispersion of the T-spin for the eigenmodes of a bianisotropic metamaterial, in which a continuous transition from $\hat{S} \cdot \hat{z} > 0$ to $\hat{S} \cdot \hat{z} < 0$ is illustrated.

T-spin Dynamics in Realistic Metamaterial

In the experiments, we adopt an unbalanced split-ring resonator (USRR) structure as the building block to construct the bulk metamaterial. The detailed information of the metamaterial and the USRR structure are shown in Fig. 2a and Fig. 2b. The unit cell lattice constants in x , y and z directions are 12mm, 12mm, and 5mm, respectively. Two identical USRRs made of copper are fabricated on both sides of 1mm thick FR4 substrate (a printed-circuit board, whose dielectric constant is 4.3 with loss tangent 0.025). For more details of the design, please refer to the supplementary information section III.

With the orientation of USRRs indicated in Fig. 2b and for the TM-type mode (magnetic field along z direction and electric field in the x - y plane) that we are interested in, only four effective parameters are involved, i.e., ϵ_x , ϵ_y , μ_z and χ_{zx} , whose effective values are extracted from the transmittance and reflectance by a slab made of one-layer USRRs, through the parameter-retrieval approach (Fig. 2c)³⁷⁻³⁸. The bianisotropy vector for this specific configuration is given by $\bar{C} = -\hat{y}\chi_{zx}$, which is indicated in Fig. 2b. The dispersion relation for the TM mode is given by $\frac{\epsilon_x}{\epsilon_y}k_x^2 + k_y^2 = \omega^2(\epsilon_x\mu_z - \chi_{zx}^2)$. In Fig. 2d, we present the propagation index of the mode traveling in the x direction with and without the bianisotropy term. There

exists a forbidden band, as indicated by the shadowed region in Fig. 2c and Fig. 2d, corresponding to negative n_x^2 . It is seen that the medium would be transparent without χ_{xx} in most of the forbidden band of the metamaterial, i.e., the upper half of the forbidden band (above 3GHz) arises from the ME coupling. For the sake of completeness, the dispersion and the isofrequency surface of the metamaterial of the band right above the bandgap are also calculated using the retrieved constitutive parameters, which are presented in Fig. 2e and Fig. 2f. In these two figures, different T-spins are indicated in purple and blue colors, respectively.

In order to measure the T-spin of the propagating mode, we carry out near field measurement across the sample surface. In the measurement, a bulk metamaterial composed of $24 \times 12 \times 10$ USRR unit cells is fabricated. The TM mode is excited inside the bulk through a feeding waveguide at the center of bulk surface perpendicular to x direction. The E-field distribution is measured at a distance 5mm above the top surface of the bulk medium (For the detailed configurations, please refer to the supplementary information section IV). The measured distributions of E_x and E_y of the TM mode at 3.6 GHz are shown in Fig. 2g. It is clearly seen there exists $-\pi/2$ phase difference between E_x and E_y , i.e., the electric field rotates in the plane containing \bar{k} , and hence the presence of transverse SAM is experimentally confirmed. Fig. 2h shows the simulation results on the polarization state. The simulation shows that the field is strongly inhomogeneous due to the localized resonance in individual USRRs, while this local inhomogeneity is not present in the measurement. This is because the probe has a finite size, which records locally averaged field. Nonetheless, the overall phase patterns for both electric field components are in good agreement between the simulation and the experiment.

The presence of T-spin in the bulk mode supported by the bianisotropic metamaterial provides opportunity for spin-dependent asymmetric excitation of the mode. In Fig. 3a, we show the schematic of the excitation of the bulk mode, where a beam of circular polarization is incident onto the sample edge to excite the bulk wave propagating along $+\hat{x}$ direction. From previous analysis, the T-spin excited into the bulk ($\hat{k} = +\hat{x}$) would have its SAM pointing to the $+\hat{z}$ direction, which matches that of LCP incidence. In Fig. 3b, we show the power collected by the receiver located at the right-hand side of the bulk. Both the simulated and measured results show that the detected signal is strong with LCP incidence, with the peak power observed around 4GHz, where the polarization matching between the LCP and the T-spin is optimized (for more details please refer to the supplementary materials). However, for the RCP incidence, the excitation is very weak due to the mismatch of the incident spin and the T-spin of the bulk mode. Thus, we directly confirm the spin-selective excitation of the bulk mode through the measurement.

The Interface Modes

The preceding theoretical analysis shows that a very large bianisotropy can result in insulating phase for photons. Interestingly, when two metamaterials with opposite bianisotropy form an interface, there exist interface state that shows robust propagation, though this robustness is not of topological origin.

Assume an interface is formed by two metamaterials with opposite bianisotropy while all other parameters being the same ($\bar{\epsilon}_1 = \bar{\epsilon}_2$, $\bar{\mu}_1 = \bar{\mu}_2$ and $\bar{\chi}_1 = -\bar{\chi}_2$). This corresponds to reversing the USRR ring-split orientation on one side of the interface relative to the other side,

as shown in Fig. 4a. Due to the fact that the metamaterials do not exhibit z rotational symmetry in the x - y plane, the interface mode depends on the orientation of the interface. Without losing generality, we assume the interface is in the x - z plane while the orientation of the bulk metamaterial (represented by the local coordinate x' - y') forms an angle ϕ with the interface, as shown in the insets of Fig. 4a. By solving the boundary problem (Supplemental Materials), we obtain

$$k_y = \frac{-k_x(\varepsilon_x - \varepsilon_y)\sin\phi\cos\phi + i\delta\omega\chi\varepsilon_y\cos\phi}{\varepsilon_x\sin^2\phi + \varepsilon_y\cos^2\phi}, \quad (1)$$

with $k_x = \omega\sqrt{\mu_z(\varepsilon_x\sin^2\phi + \varepsilon_y\cos^2\phi) - \chi^2\sin^2\phi}$, and $\delta = \pm 1$ for waves in $y > 0$ and $y < 0$ regions. Equation (1) shows that the propagation of the interface modes can be manipulated through tuning the two bulk media's orientation angle (ϕ). In particular, for $\varepsilon_x\mu_z < \chi^2$, with $\phi=0$ and $\phi=\pm\pi$, k_x is real; but with $\phi=\pm\pi/2$, both k_x and k_y become imaginary (or zero). Because the imaginary part of k_y has to be positive to guarantee the decay of interface modes in the $y > 0$ region, the interface modes can only exist within a limited range of ϕ . For given constitutive parameters, the dispersion and in particular the cutoff of the surface mode are ϕ -dependent (Supplementary Material). In Fig. 4b, we show the dispersion curves of these interface states with different ϕ . A variation of the cutoff frequency for the interface modes by tuning ϕ is clearly observed. For $\phi=0$, the H_z distribution at 3GHz is shown in Fig. 4c, wherein well-confined interface mode is observed. However, with $\phi=\pi$, according to equation (1), no surface modes could exist. In the experiments, the transmittance of the interface modes with $\phi=0$ and $\phi=\pi$ is measured and shown in Fig. 4d. It is observed that the transmission with $\phi=0$ occurs above 3GHz, which is consistent with

our numerical evaluations in Fig. 4b. However, with $\phi=\pi$ no efficient transmission is observed, which again confirms our theoretical analysis.

The measured transmittances for the interface mode with different number of bends are shown in Fig. 4f. It is observed that the transmission is very efficient for frequency above 3.2GHz, which agrees with our numerical evaluation in Fig. 4b. Importantly, the transmittances with different number of bends are almost the same, indicating highly robust transmission of the edge mode. And, the robustness of the zero-indexed transmission³⁹ is verified by the transmittances shown in Fig. 4f. It is interesting to note that in contrast to possession of T-spin in the bulk mode, it is found that the interface mode is linearly polarized, as shown in Fig. 4a. The linear polarization of the interface modes is enforced by the boundary condition between two media of opposite bianisotropy (Supplementary Materials). This also indicates the exact cancellation of the transverse spin from the contribution of the evanescent wave vector and that of bianisotropy.

Conclusion

In conclusion, we have demonstrated T-spin for bulk modes inside a medium with orthogonal ME coupling. A direct mapping from SPP modes to bulk modes shows that the ME coupling in a bulk medium can act equivalently to the evanescent wave vector of a surface wave in forming the T-spin. The T-spin is directly confirmed by both the experimental measurement and numerical simulations. We further show the spin selective excitation of the bulk mode, T-spin induced insulating phase and the corresponding edge mode. The low-index-induced robust transmission of the interface modes with tunability by the orientation angle of the USRRs

provides a promising approach for the on-chip guidance of photonic power. In contrast to previously studied T-spin in evanescent waves, our work has provided a new approach to construct the T-spins in the bulk mode of metamaterials. Our work may facilitate many photonic applications, such as spin-selective absorption and extinction, polarization detection, asymmetric emission and guidance, as well as on-chip manipulation of photons.

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Author Contributions

L. P. conceived the idea. L. P. and S. Z. proposed the physical concept, formulated the theory, and planned the experiments. L. P., L. D., K. W. and L. Z. conducted the experiments. F. G., G. W., Y. Y. and H. C. participated in the data processing and analysis. L. P., S. Z., F. G. and H. C. discussed the results and wrote the manuscript.

Competing Interests

The authors declare no competing interests.

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Figures and Figure Legends

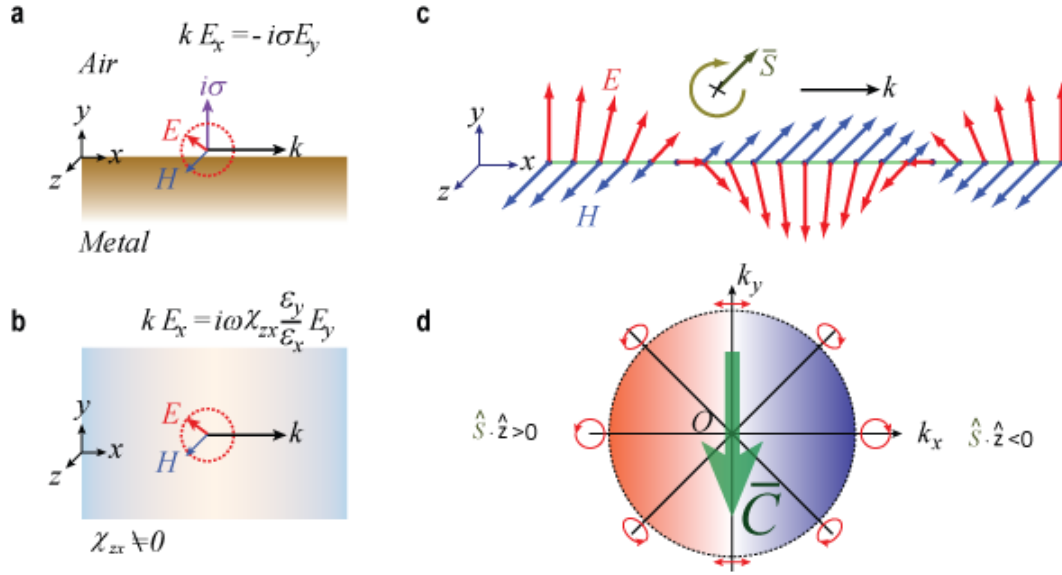


Figure 1. T-spins in the bulk mode of a homogeneous material. **a**, T-spin is excited due to the imaginary wavevector for the SPPs. **b**, T-spin is excited due to the non-zero ME coupling ($\chi_{zx} \neq 0$). **c**, T-spin dynamics of light ($\chi_{zx} > 0$). In the calculation, $k_y = 0$ is assumed. **d**, The spatial dispersion of the T-spin in bulk metamaterials. In the calculation, $\vec{C} = -\hat{y}\chi_{zx}$ is assumed.

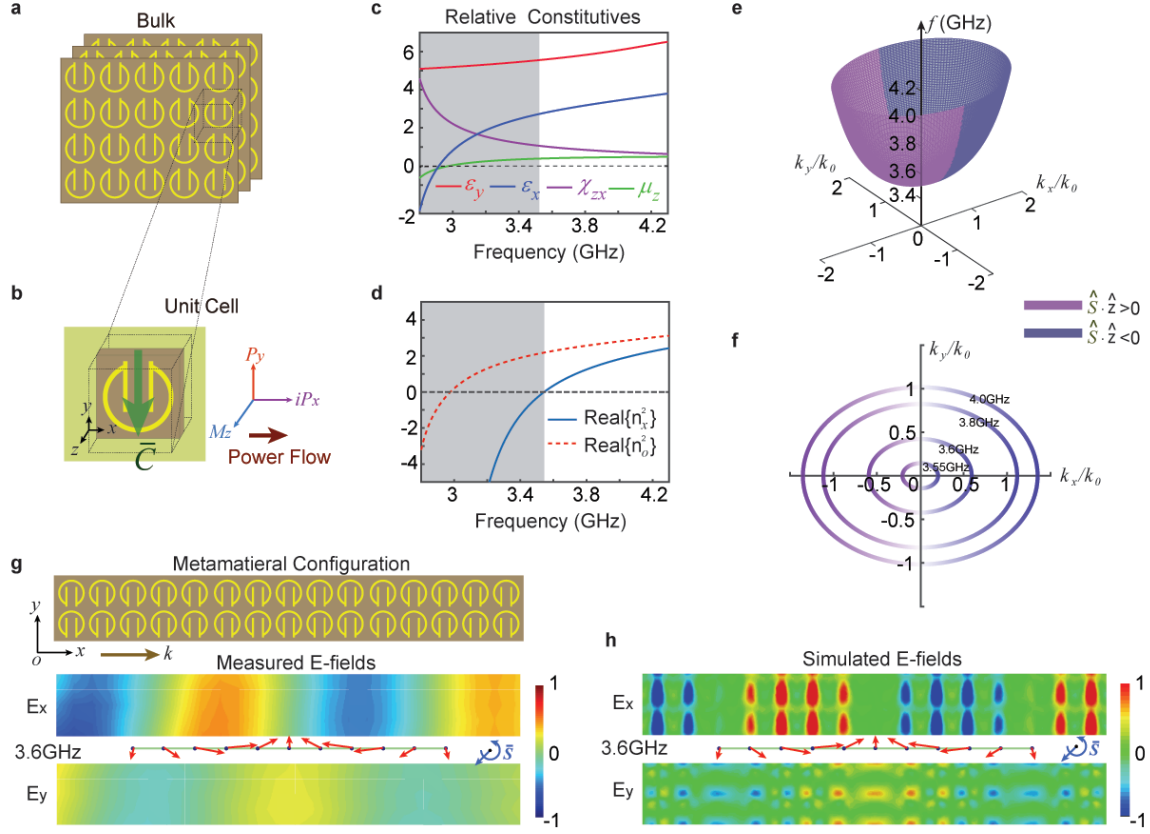


Figure 2. Demonstration of T-spin in a homogeneous metamaterial. **a**, The metamaterial is made by a USRR array (3D). **b**, Polarization and magnetization on an individual USRR. **c**, The retrieved effective parameters (ϵ_x , ϵ_y , μ_z and χ_{zx}) relevant to the TM-type mode. The shadow region represents the forbidden band. **d**, Calculated dispersion curves for $n_o^2 = \epsilon_y \mu_z$ (without bianisotropy) and $n_x^2 = \epsilon_y \mu_z - \epsilon_y \chi_{zx}^2 / \epsilon_x$ (with bianisotropy). In the range above 3GHz, $\text{Re}\{n_o^2\} > 0$ and $\text{Re}\{n_x^2\} < 0$, indicating the T-spin induced insulating effect. For **c** and **d**, the imaginary parts are negligible and not shown. **e**, Isofrequency surface of the metamaterial in the band of interest. **f**, Dispersion curves for different frequencies. **e** and **f** are evaluated with the constitutives shown in **c**. In **e** and **f**, $\hat{S} \cdot \hat{z} > 0$ and $\hat{S} \cdot \hat{z} < 0$ T-spins are indicated in different colors. **g** and **h**, Measured and simulated electric field distribution at 3.6GHz. In **g** and **h**, the rotation of the electric field and the SAM are schematically shown.

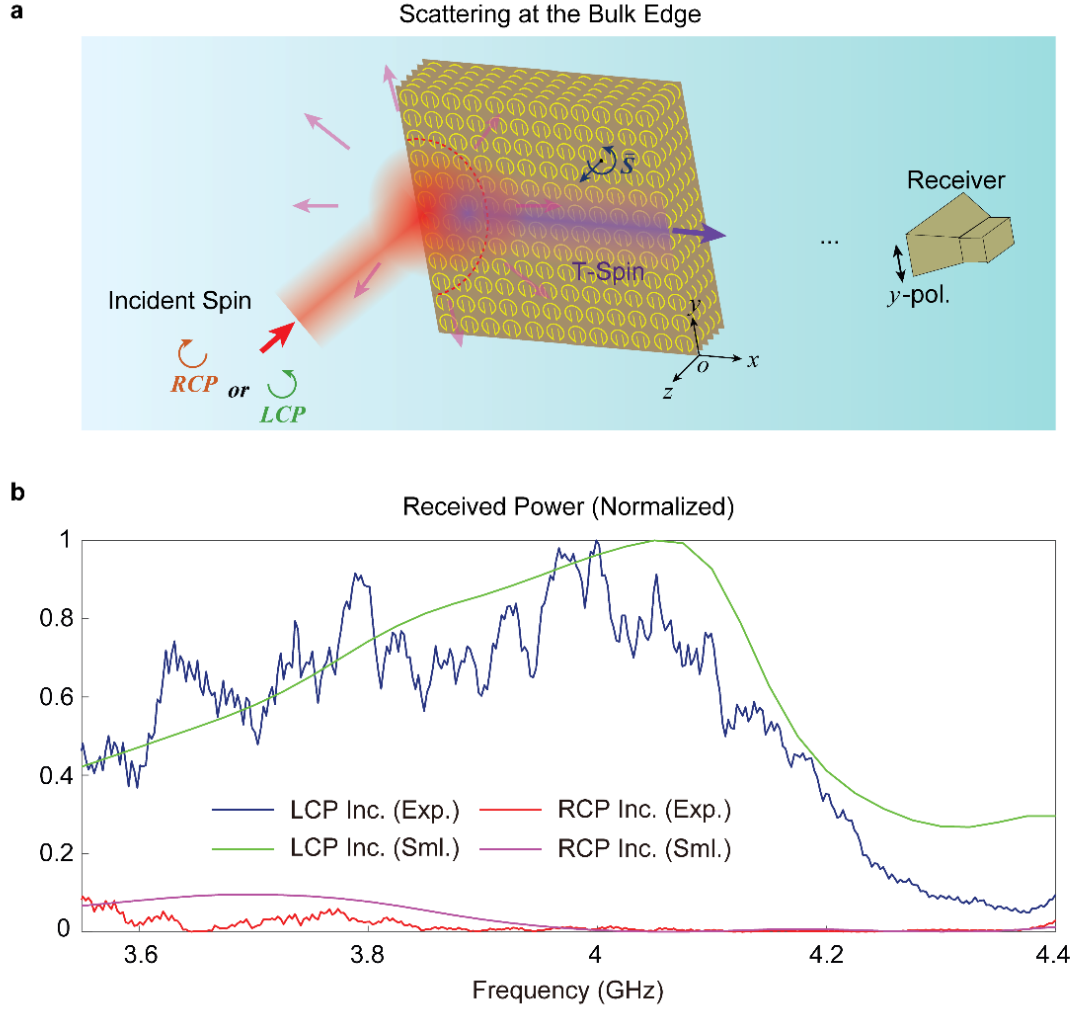


Figure 3. Spin locked scattering from a finite-sized bianisotropic metamaterial. a, Schematic of scattering from a finite-sized bulk metamaterial made of $12 \times 12 \times 6$ USRRs. In the experiments, the power receiver is placed on the right-hand side. **b,** The received power spectrum in both the measurements and simulations. The results are both normalized.

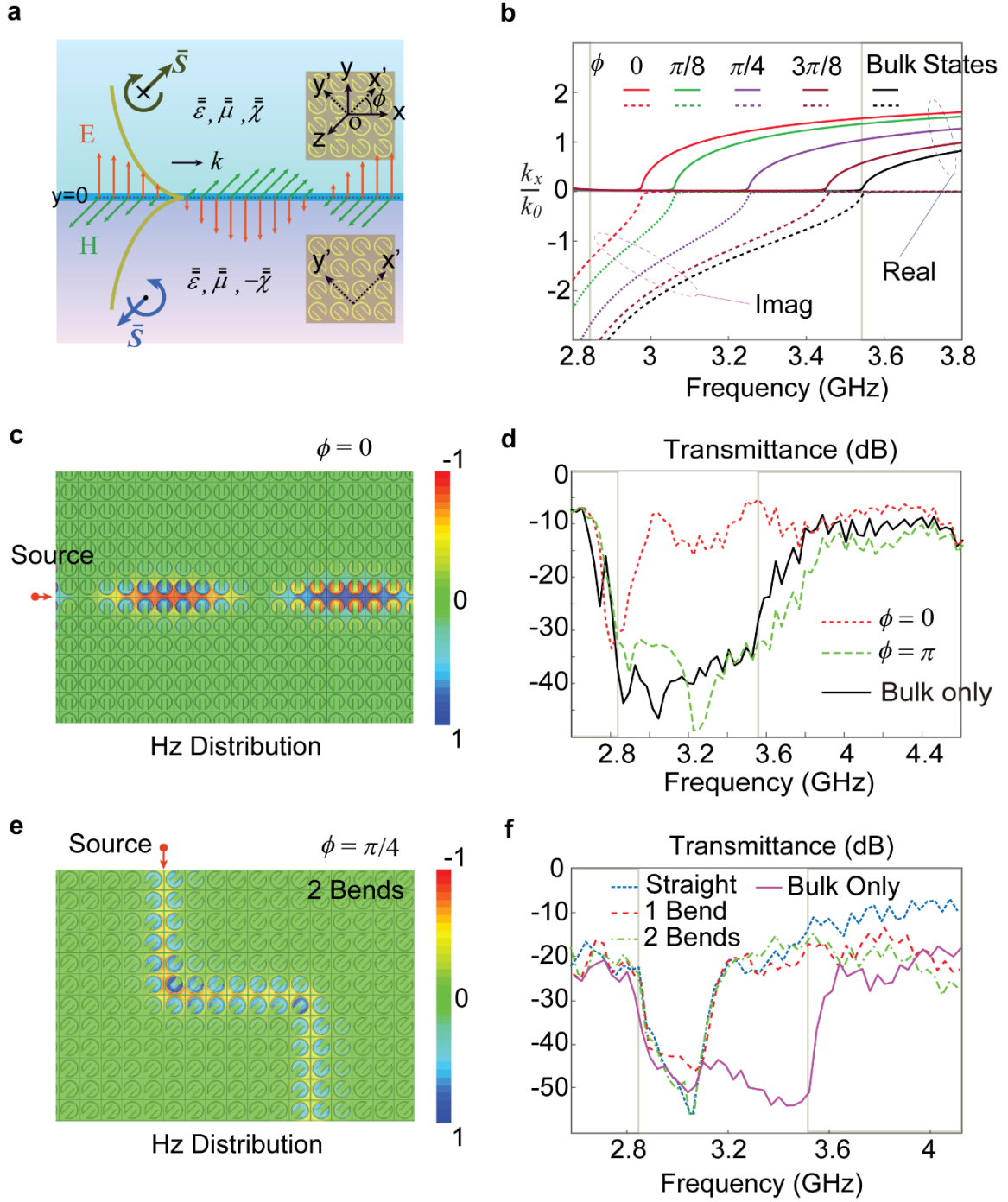


Figure 4. Compensation of T-spins on an edge and propagation of interface modes. **a**, Linearly polarized modes on an interface between two bianisotropic bulks with opposite orientations. **b**, Numerically calculated dispersion for the interface mode. The upper and lower bounds for the forbidden band are indicated. **c**, Simulated H-field distribution for the interface

mode with $\phi = 0$. **d**, Measured transmittance for $\phi = 0$ and $\phi = \pi$. For better comparison, the transmittance for the bulk metamaterial is also shown. **e**, Simulated H-field distribution for the $\phi = \pi/4$ interface mode with two-bends passage at 3.2GHz. Because k_x is a small, there is almost no back-reflection. **f**, Measured transmittance for the $\phi = \pi/4$ interface mode for interface configurations with different number of bends but the same length. For **d** and **f**, the details of the experimental setup, as well as the configurations of the three passages, can be found in the supplementary.